Indoor Air 1999; 9: 165–179

INDOOR AIR
ISSN 0905-6947

Perceived Air Quality, Sick Building Syndrome (SBS) Symptoms and Productivity in an Office with Two Different Pollution Loads

PAWEL WARGOCKI*, DAVID P. WYON, YONG K. BAIK, GEO CLAUSEN AND P. OLE FANGER

Abstract Perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity were studied in an existing office in which the air pollution level could be modified by introducing or removing a pollution source. This reversible intervention allowed the space to be classified as either non-low-polluting or low-polluting, as specified in the new European design criteria for the indoor environment CEN CR 1752 (1998). The pollution source was a 20-year-old used carpet which was introduced on a rack behind a screen so that it was invisible to the occupants. Five groups of six female subjects each were exposed to the conditions in the office twice, once with the pollution source present and once with the pollution source absent, each exposure being 265 min in the afternoon, one group at a time. They assessed the perceived air quality and SBS symptoms while performing simulated office work. The subject-rated acceptability of the perceived air quality in the office corresponded to 22% dissatisfied when the pollution source was present, and to 15% dissatisfied when the pollution source was absent. In the former condition there was a significantly increased prevalence of headaches ($P=0.04$) and significantly lower levels of reported effort ($P=0.02$) during the text typing and calculation tasks, both of which required a sustained level of concentration. In the text typing task, subjects worked significantly more slowly when the pollution source was present in the office ($P=0.003$), typing 6.5% less text than when the pollution source was absent from the office. Reducing the pollution load on indoor air proved to be an effective means of improving the comfort, health and productivity of building occupants.

Key words Perceived air quality; Sick Building Syndrome (SBS) symptoms; Productivity; Source control; Low-polluting building; Non-low-polluting building.

Received 27 April 1999. Accepted for publication 27 May 1999

Introduction

Increased pollution load on indoor air due to pollutants emitted by building materials and furnishing can cause complaints of poor air quality (Fanger et al., 1988; Thorstensen et al., 1990; Pejtersen et al., 1991; Bluyssen et al., 1996). It can negatively affect the health of building occupants by increasing the prevalence of mucous membrane, cutaneous or general symptoms (Mølhave et al., 1986; Berglund et al., 1992b; Mendell, 1993) usually referred to as Sick Building Syndrome (SBS) symptoms (World Health Organization, 1982). The new European report CEN CR 1752 (1998) formulates modern design criteria for the indoor environment which address the above-mentioned problems. It specifies how the required ventilation rate can be calculated based on the sensory pollution load, acknowledging the building as a source of pollution. The CEN CR 1752 document strongly recommends selecting materials so that the building can be characterized as low-polluting, with a sensory pollution load of 0.1 olf/m^2 floor area from the building itself. If no selection of materials takes place, the building is characterized as non-low-polluting, with a sensory pollution load of 0.2 olf/m^2 floor area or more.

Control of pollution sources as recommended by CEN CR 1752 is not a new measure for improving the air quality in buildings. Source control was recommended by Pettenkofer (1858) already in the nineteenth century and has been the philosophy behind legislation to decrease outdoor air pollution for several decades. It is nevertheless important to study how efficient this measure can be in relation to health symptoms and productivity since rather limited experimental data exist on these issues.

*International Centre for Indoor Environment and Energy, Technical University of Denmark, Building 402, DK-2800 Lyngby, Denmark, Tel: +45 45 25 40 11, Fax: +45 45 93 21 66, E-mail: pw@et.dtu.dk. *Author to whom correspondence should be addressed*

Some studies have shown that reducing the pollution load on indoor air can decrease the number of persons dissatisfied with the perceived air quality and the prevalence of SBS symptoms: in an intervention study in a naturally ventilated office building in Denmark that had been identified as a problem building, the pollution load on the air was reduced by substituting a polyamide bouclé floor carpet, which had been found to be an important source of sensory pollution, by flooring made of polyolefine tiles, selected in the laboratory as being the lowest polluting floor material among nine different floor materials tested (van Beuningen et al., 1994). Following the intervention, the air quality caused less dissatisfaction, as assessed both by an independent panel of subjects and by occupants of the building. Wargocki and Fanger (1997) studied the air quality in three groups of naturally ventilated offices in Denmark. The three groups of offices were similar and differed only in terms of the pollution load on the air; they had three types of floor material: felt carpet, linoleum and floor tiles made of polyolefine. The perceived air quality assessed by an independent panel of subjects upon entering the offices and after 1 h of occupation indicated less dissatisfaction in the offices with the polyolefine floor tiles, which also had the lowest pollution load on the air. In a longitudinal study of the personnel in two mechanically ventilated schools in Sweden, the prevalence of eye symptoms, face rashes, headache and abnormal tiredness decreased when wall-to-wall carpet, anticipated to be a considerable source of air pollution, was removed and replaced by hard polyvinyl chloride (PVC) flooring materials (Norbäck and Torgén, 1989). A significant decrease of adverse perceptions and SBS symptoms among occupants was observed in an office building in Denmark which was renovated by substituting an old polyamide bouclé carpet with new low-emitting vinyl and by renovating the ventilation system (Pejtersen et al., 1999).

Little is known of the direct effects of air pollution on human performance in office buildings. No impaired performance of neurobehavioural tests of short duration (Baker et al., 1985) was observed in studies by Otto et al. (1992, 1993) of healthy subjects exposed to a mixture of 22 volatile organic compounds (VOCs) characteristic of pollutants emitted from building materials in Denmark (Mølhave, 1982; Mølhave et al., 1986), even though the concentrations were as high as 25 mg/m^3, which is the highest concentration found in practice in new Danish houses (Mølhave and Møller, 1978). On the other hand, chamber exposure to the VOC mixture mentioned above at concentrations of 5 and 25 mg/m^3 decreased memory for digits in a standard digit span test when subjects who were healthy but claimed to suffer from typical indoor climate symptoms were tested instead (Mølhave et al., 1986). Toluene levels of 100 ppm were shown to significantly reduce manual dexterity, performance of a colour discrimination task, and the accuracy of visual perception (Bælum et al., 1985). Although toluene is one of the pollutants most frequently emitted by building materials, toluene concentrations in non-industrial spaces are usually 1,000-fold lower (Brown et al., 1994), so the results of Bælum et al. are of little relevance for indoor air quality in offices to which most people are exposed. In the classical series of studies performed by the New York State Commission on Ventilation (1923), ventilation rates were reduced until the levels of carbon dioxide (CO_2) had risen to 3,000–4,000 ppm, levels which would normally be taken to indicate a substantially increased pollution load on the air, but even under these conditions no effect was found on the performance of simulated office work.

In spite of the results presented above, there is good reason to believe that poor air quality causing SBS symptoms such as fatigue and headaches may negatively affect human performance: Nunes et al. (1993) observed impaired performance of the computerized continuous performance task and symbol-digit substitution task among office workers who reported any SBS symptoms in a mechanically ventilated building in Canada (Wyon, 1996). On the other hand, no effects were observed on the performance of four psychological tests measuring reaction time, short-term memory vigilance and hand steadiness when subjects occupied office buildings in Sweden diagnosed as "healthy" or "sick" (Berglund et al., 1992a). In this study, however, no significant difference was observed in the prevalence of SBS symptoms between subjects exposed to buildings assumed to be "sick" or "healthy". The review by Leinster and Mitchell (1992) claimed that building-related symptoms negatively affected self-reported productivity, but only if they averaged two symptoms per person or more. Self-reported productivity was found to be linked to the prevalence of SBS symptoms in the questionnaire survey in office buildings in the UK (Raw et al., 1990) and in a study of an office building in the USA (Hall et al., 1991).

Taking into account the information summarized in the above paragraphs, it is reasonable to expect that decreased pollution load on indoor air will lead to improved air quality, and thus to reduced prevalence of SBS symptoms. This, in turn, may have a positive effect on the individual performance of occupants, and thereby lead to a general increase in productivity. The objective of the present study was to investigate this mech-

anism by studying whether the perceived air quality, SBS symptoms and performance of the same group of subjects working in an office are influenced by a difference in pollution load corresponding to the difference between a low-polluting and a non-low-polluting building, as defined by CEN CR 1752 (1998).

Methods

Approach

The air pollution level in an office space was modified by introducing or removing a pollution source while all other environmental parameters were kept unchanged. Impartial female subjects were exposed in the office with the pollution source present and absent. They were unaware of any intervention since the pollution source was placed behind a partition. The subjects assessed the perceived air quality, indoor climate and SBS symptoms upon entering the office and on several occasions during each exposure in the office. Following the exposure period, the subjects left the office and re-entered it after a short time to re-evaluate the perceived air quality. During each exposure in the office, the subjects performed tasks simulating office work and were exposed to a diagnostic psychological test battery measuring their performance. These measures were used as estimates of the productivity of subjects at two levels of air pollution. Subjects were able to remain thermally neutral, and were asked to adjust their clothing whenever they felt too warm or too cold, during each exposure in the office. The subsection on Experimental Procedures and Figure 4 provide a detailed plan of the experiment.

Facilities

The study was carried out in an ordinary but low-polluting office space with two 3-m-wide windows facing east (Figure 1) and the floor consisting of tiles made of polyolefine, known from previous studies to be a low-polluting floor material (van Beuningen et al., 1994). The office had a floor area of 36 m^2 and a volume of 108 m^3 ($L \times W \times H = 6 \times 6 \times 3$ m).

The office was divided into two smaller spaces by means of a partition (Figure 1). The partition was 2 m high so that the air from one space could easily mix with the air from the other, while constituting a sight-barrier preventing people occupying one space from seeing what was placed behind the partition in the other space. Both spaces had access to windows. In one space, equipment supplying and conditioning the air was located, and there was room for an extra pollution source to be placed. The air was supplied by an axial fan mounted in the window and conditioned by an electric oil-heater and a steam humidifier. There was no cooling but the outside temperature made this unnecessary. In the other space subjects sat at six workstations, each consisting of a table, a chair, a desk lamp and a personal computer (PC). Wooden stairs (not shown in Figure 1), used for a step exercise during the exposure, were also located in this space. The air in the two spaces was efficiently mixed by several small fans.

Subjects

Thirty subjects were recruited among 58 applicants to participate in the present experiment. The subjects were recruited based on the following criteria: female gender, familiarity with a PC, impartiality to the office in which the study was carried out, and absence of chronic diseases, asthma, allergy and hay-fever. However, among the subjects selected based on the above criteria, a few dropped out prior to the start of the experiment, and it was necessary to include one subject with asthma and one with hay-fever among the substitutes. The 30 female subjects participating in the pres-

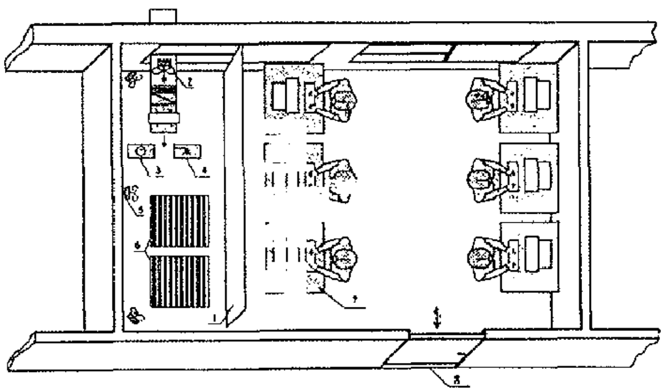

Fig. 1 Experimental set-up in the office in which the investigation was carried out: 1-partition, 2-axial fan with damper and silencer, 3-electric heater, 4-electric steam humidifier, 5-mixing fan, 6-samples of carpet hanging on stainless steel racks, 7-workstation consisting of a table, a desk lamp, a personal computer (PC) and a chair, 8-exhaust aperture (a slot under the door). In the figure, the subjects are sitting at the workstations and the pollution source is present in the office (carpet behind the partition)

ent experiments were all students, aged 20–31 years ($\mu=24$, $\sigma=\pm3$). Twenty-three subjects were non-smokers, 23 subjects had a history of SBS symptoms, i.e., reported that within a year prior to the experiment they had experienced at least twice per month at least one mucosal, cutaneous or general symptom, and 11 subjects reported that they considered themselves to be more sensitive than most to poor air quality. All of the above information was obtained from a questionnaire distributed to applicants during recruitment. The subjects were not examined medically.

During the week preceding the experiment, subjects received 5 h of training in the performance tasks and the performance test battery subsequently used during the experimental exposure. They were also instructed on how to fill out the questionnaires used to obtain subjective responses. During training sessions, subjects were kept blind to the exposure conditions and were not informed that the sessions were only for practice. The subjects who participated in the experiment also took an olfactory test comprising a ranking test with n-butanol at 4 concentrations: 10, 80, 320 and 1,280 ppm (vol/vol); a matching test with n-butanol, 2-butoxyethanol and 2-butanone, each compound being at a concentration of 640 ppm (vol/vol) and a "blank" exposure with no chemical compound according to ISO (1988, 1993). The ranking test was used to evaluate the ability of subjects to classify different odour intensities and the matching test to assess their ability to identify several stimuli of odour. Subjects had on average 82% correct ranking and 78% correct matching. Nobody was excluded from participating in the study based on the results of olfactory tests.

The subjects were paid a salary for participation in the experiment at a fixed rate per hour. To increase their motivation, they were also paid a bonus of up to 20% of the total salary, depending on their performance. All 30 subjects completed all experimental sessions.

Test Conditions

The experiment was carried out in the office with two different pollution loads, one corresponding to a non-low-polluting building (~0.2 olf/m^2 floor area) and another corresponding to a low-polluting building (~0.1 olf/m^2 floor area) according to CEN CR 1752 (1998). To modify the air pollution level in the office, a pollution source was introduced in the office behind the partition or was removed from the office, and these two exposure conditions are subsequently referred to in the paper as the office with pollution source present and absent, respectively. The pollution source consisted of samples of a tufted bouclé carpet with 100% polyamide fibres and latex backing, taken from an office building in Denmark in which an intervention study had previously been carried out, and where it had been situated for 20 years. This study showed that occupants' adverse perceptions (i.a., the perception of stuffy air, unpleasant odour and poor acceptability of air quality) and symptoms (i.a., dry, irritated nose and throat, and difficulty in thinking clearly) were significantly reduced by the intervention which partly consisted of replacing the carpet with low-emitting floor material (Pejtersen et al., 1999). The samples of carpet with a total surface area corresponding to the floor area of the entire office (36 m^2) were attached back-to-back and the edges were protected so that the backing of the carpet was not exposed to the air during experiments. The samples of carpet hung behind the partition (Figure 1) on stainless steel racks on wheels for easy transportation. All other environmental parameters, including an operative temperature of 24°C, a relative humidity (RH) of 50%, an air velocity below 0.2 m/s, a noise level of 42 dB(A) (without occupants and their activities in the office) and a ventilation rate of 10 L/s per person (1.7 L/s per m^2 floor area) were kept constant independently of whether the pollution source was present or not. The office was illuminated by daylight through the windows with a total glass area of ca. 5.5 m^2. Since the experiments were carried out in the afternoon and the windows faced east, no direct sunlight could enter the office. The illumination level could, if needed, be increased by any subject who felt it was too dark by switching on the desk lamp provided at each workstation.

Measurements

Physical and Chemical Measurements. The temperature and relative humidity of the air, the concentration of CO_2, and the toluene equivalent concentration of total volatile organic compounds (TVOC) were measured continuously at each workstation and in the supply air. The noise level was measured continuously using a meter located at the central point of the space occupied by the subjects. The ventilation rate and ventilation effectiveness were measured repeatedly during the experiment. Duplicate 5-h samples of air were collected at the central point of the space occupied by the subjects and in the supply air for subsequent gas chromatography/mass spectrometry (GC/MS) analyses; sampling was carried out on two successive days with the pollution source present and absent in the office. The air samples were collected on silica gel tubes coated with 2,4-dinitrophenylhydrazin for measuring the concentrations of formaldehyde and on Tenax-TA tubes in order to quantify 25 VOCs with the highest

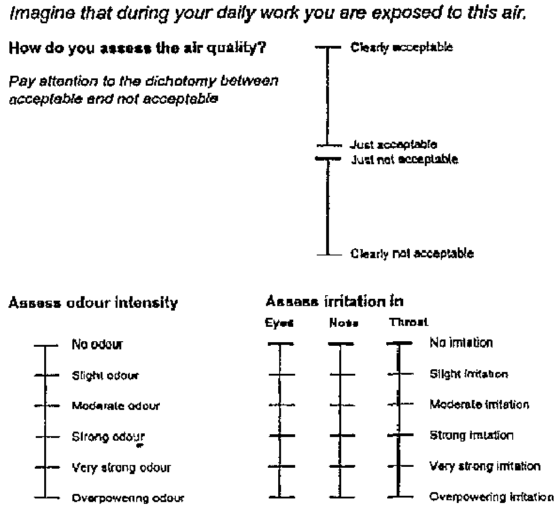

Fig. 2 Questionnaire used to assess perceived air quality

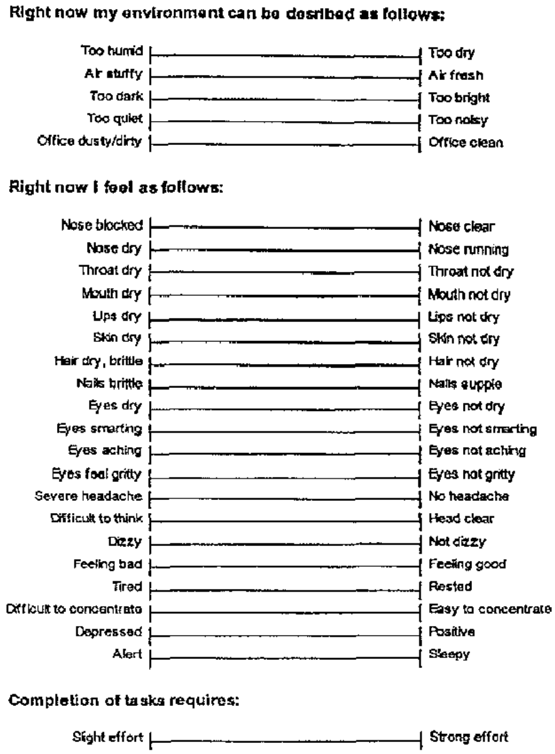

Fig. 3 Visual-analogue scales (VAS) used to measure general perception of the environment, SBS symptoms and self-performance

concentrations. GC/MS analyses of the air samples were carried out with the following accuracy: the relative standard deviation of the measured concentrations of formaldehyde was ±10% but not less than 1.9 $\mu g/m^3$ and the relative standard deviation of the measured concentrations of VOCs was ±10% but not less than 0.12 $\mu g/m^3$. Parallel to the collection of samples for GC/MS analyses, the concentration of ozone was measured both in the office air and in the supply air taken from outdoors.

Subjective Measurements. The questionnaire used to obtain subjective sensations included questions regarding perceived air quality, general perceptions of the environment, SBS symptoms and thermal comfort. The perceived air quality was assessed using continuous scales (Figure 2) describing the acceptability of air (Gunnarsen and Fanger, 1992), the intensity of odour (Yaglou et al., 1936) and irritation of the eyes, nose and throat (Yaglou, 1955). General perceptions of the environment and SBS symptoms were evaluated using visual-analogue scales (VAS) (Figure 3) – horizontal lines without graduation with two vertical dash lines marking the extreme points of the scale, each with defined end labels (Wyon, 1994). Thermal comfort was assessed by answering questions pertaining to thermal sensation and draught (ASHRAE, 1997).

Measurements of Performance. Throughout the exposure in the office, subjects performed psychological tests and carried out simulated office work. Their performance of these tasks is assumed to be indicative of the productivity of the subjects under similar conditions.

Four different sets of computerized tasks from a Danish language version of the Walter Reed performance assessment battery (PAB) were used as psychological tests (Thorne et al., 1985). Each set comprised eight tasks which were presented to subjects on a computer screen in the following order: two-letter search (a visual search and recognition task), two-column addition (a subject-paced mental arithmetic task), logical reasoning (an exercise of transformational grammar), serial addition/subtraction (a machine-paced mental arithmetic task), Stroop[1] (a test of response due to perceptual/linguistic interference), running memory (a measure of immediate memory with a distractor), six-letter search (a visual search and recognition task) and code substitution (a paired associate learning task). It took subjects approximately 20 min to complete each

[1]A Stroop test presents a series of words, each the name of a colour, but each presented in a colour that may be the same or different, creating a conflict when subjects are asked to respond to the colour in which each word is presented rather than to the colour named by the word.

set of tasks. Speed (reaction time, interstimulus interval and stimulus duration) and accuracy (number of errors) were registered by the computer during the presentation of these tasks and were used as measures of subjects' performance.

Typing text on a PC, addition of numbers and an open-ended test of knowledge and recall were used to simulate office work. In the typing task, subjects retyped a printed text on a PC, using the standard text editor. Four different texts of similar difficulty were used, each so long that it was impossible to finish in the time available. They were typed by the subjects at their own pace and each text was typed for 47 min. The average number of characters typed per min (speed) and the total number of errors (accuracy) were used as measures of performance. In the addition task, five two-digit numbers, random but excluding zeros, were printed in columns (Wyon et al., 1975). Subjects attempted to add as many columns as possible during a 25-min period. The average number of such units completed per h (speed) and the percentage of correctly executed operations (accuracy) were used as measures of performance. In the knowledge and recall test, subjects wrote down as many familiar Danish male or female names as possible beginning with either of 2 given letters. Four different tests were administered to subjects, two per exposure, with 25 min to complete each of them. The answers were scored in terms of their originality. For each name in each version, the probability (P) of its occurrence was calculated by dividing the number of times the answer was given by different subjects by the total number of subjects. This probability was then transformed into bits ($Log_2(1/P)$), according to information theory, and finally the scores in bits were analysed (Wyon, 1969).

Experimental Procedure

The experiment was carried out during the two first weeks in June 1998, each week on five days from Monday to Friday, and each day for 5 h in the afternoon, from 13:00 to 18:00. The exposure conditions were completely randomized during two weeks of experiments, except that each subject experienced both conditions, and the performance tests and tasks simulating office work were presented to subjects completely at random in order to eliminate possible bias due to confounding of test versions with exposure conditions. Subjects occupied the office in 5 groups of 6 subjects each. Each group was randomly assigned to a weekday and was then exposed to the two conditions on the same weekday of two successive experimental weeks to avoid any influence of weekday on the within-subject difference between conditions.

Figure 4 shows in detail the schedule for each ex-

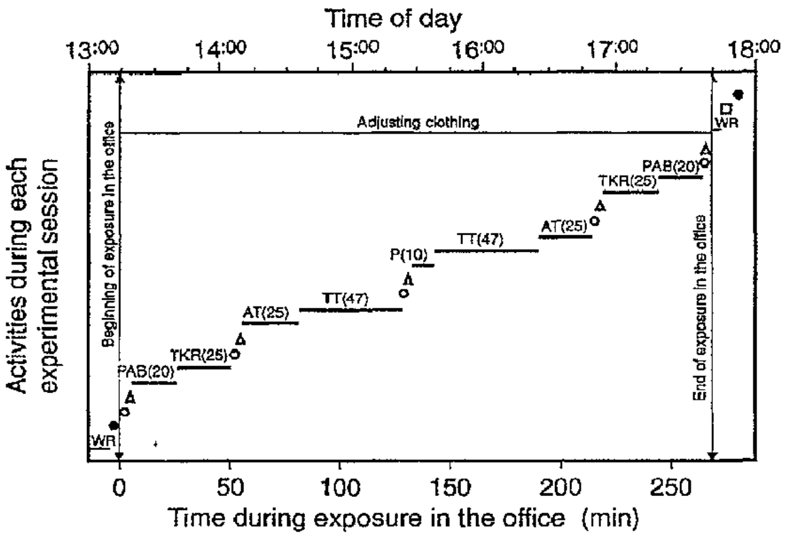

Fig. 4 Schedule for each experimental session. ●: assessments of the air quality outdoors before and after exposure in the office. O: subjective assessments indoors (air quality, SBS-symptoms, thermal comfort). △: walking over a set of 4 steps. □: assessments of the air quality in the office shortly after exposure. WR: assembling in waiting room before and after exposure in the office. PAB: performance assessment battery. TKR: test of knowledge and recall. AT: addition task. TT: text typing. P: pause. (20): duration of task or pause in minutes

perimental session. Before entering the office, subjects assembled in a waiting room for approximately 10 min. The subjects then went outdoors and assessed the perceived air quality. Following these evaluations, subjects entered the office. Immediately upon entering, subjects approached their workstations and assessed the perceived air quality. Once seated, they completed the remaining questionnaires describing general perceptions of the environment, SBS symptoms and thermal comfort. These evaluations were made four more times during exposure in the office (at ca. 50, 125, 215 and 265 min after entering the office) while subjects were seated at their workstations. After each evaluation, subjects walked over a set of 4 steps, each 0.2 m high, to simulate physical activity during normal office work (Arens et al., 1998). While exposed to the conditions in the office, subjects first performed the PAB, then the knowledge and recall test, followed by the addition of numbers and typing text. When the subjects finished typing, they took a 10-min break during which they stayed in the office and left it only if it was necessary to do so. After the break, subjects performed the same tests in the reverse order. In order to remain thermally neutral (mean thermal vote=0) throughout the exposure, subjects were reminded to adjust their clothing whenever they felt too warm or too cool. Whenever thirsty or hungry, subjects could consume the non-carbonated water and digestive biscuits which were available at each workstation. Exposure in the office lasted a total of 265 min. Following the exposure, subjects returned to the waiting room where they spent approximately 5 min. They then re-entered the office and after approaching their workstations they re-assessed the perceived air quality. Following this evaluation, subjects went outdoors and assessed the perceived air quality once more.

Statistical Analyses

Subjective assessments and the results of performance tasks were first tested for normality using Shapiro-Wilk's W test; the rejection region was set to be ($P<0.01$). Normally distributed data were subjected to analysis of variance in a repeated measures design using each subject as her own control or to paired t-tests (Montgomery, 1991). Data that were not normally distributed were analysed using Friedman's two-way analysis of variance by ranks or Wilcoxon's matched-pairs signed-ranks test (Siegel and Castellan, 1988).

Results

The measured levels of the general parameters describing the indoor climate inside the office are shown in Table 1. They did not deviate from the intended levels. The measurements of TVOC showed no difference between the concentrations in the office with the pollution source present or absent. The TVOC outdoors was nearly the same as indoors. However, the chemical analysis of individual compounds (Table 2) showed differences between the two indoor conditions. Acetone and acetic acid were the two compounds that occurred in the highest concentrations and these concentrations were higher when the pollution source was present in the office; likewise also for some other aldehydes, ketones and organic acids (Table 2).

Subjects remained thermally neutral during the ex-

Table 1 Average values of parameters of the outdoor air supplied to the office and the air inside the office on days when the pollution source was present and absent

Parameter	Office with pollution source absent		Office with pollution source present	
	outdoor air	office air	outdoor air	office air
Temperature (°C)	16.5	24.1	17.4	24.3
Relative humidity (%)	68	51	57	49
Air velocity (m/s)	–	0.13	–	0.14
Sound pressure without subjects (dB(A))	–	42	–	42
Sound pressure with subjects (dB(A))†	–	53	–	52
Outdoor air supply (L/s)	–	59.7	–	59.7
CO_2 (ppm)	406	964	407	953
Ozone (ppb)*	28	8	40	10
TVOC-toluene equivalent (ppm)	1.98	2.34	1.97	2.35
TVOC (GC/MS) (μg/m³)	165±50††	195±10	220±20	195±10

† the equivalent continuous sound pressure level for the whole period when the subjects were present in the office; higher values comparing to the office without subjects are due to the presence of subjects and their activities in the office; †† ±95% confidence interval; * measured only on two days with the pollution source present and absent in the office (outdoor concentration of ozone on other experimental days was on average 35–40 ppb, as measured by a meteorological station situated near the location of the experiment)

posures: the average thermal sensation recorded by the subjects was 0.2 in the office with the pollution source absent and 0.3 in the office with the pollution source present, with no tendency to increase or decrease during the exposure in the office. The difference is not significant. The average metabolic rate of subjects was estimated to be 1.3 met using measured CO_2 concentrations. It was thus slightly higher than the 1.2 met which is usually taken to be the typical activity level found in offices, this value being well above the level for relaxed sedentary persons, due to a higher physical activity and an assumed increase in metabolic rate during mental work resulting from an unconscious increase in muscle tonus (Wyon et al., 1975). The metabolic rate agrees well with the activities found in large field studies in offices (de Dear and Fountain, 1994).

Table 2 Results of the chemical measurements of the concentrations of VOCs (±95% confidence interval) in outdoor air supplied to the office (O) and in the office air (I) during two exposure situations: with pollution source present and absent in the office. In both conditions the air in the office was also polluted by bioeffluents. Concentrations in brackets are half the detection limits; they were not measured and are only estimates of the concentration calculated on the basis of relative response factors applied during analysis of sampled air; they were derived in order to estimate the I/O-ratio. If possible, 95% confidence interval for the I/O-ratio is provided as well

Compound	Odour threshold ($\mu g/m^3$) (Devos et al., 1990)	Office with pollution source absent			Office with pollution source present			Effect*
		Concentration ($\mu g/m^3$)		I/O-ratio	Concentration ($\mu g/m^3$)		I/O-ratio	
		outdoor air (O)	office air (I)		outdoor air (O)	office air (I)		
decane	$4.4 \cdot 10^3$	NI	NI	n/a	1.55±0.1	2.3±0.2	1.48±0.13	n/a
benzene	$12 \cdot 10^3$	3.25±1.08	8.5±2.55	2.62±0.78	3.25±0.29	7.15±1.27	2.2±0.39	↓
ethylbenzene	12.9	4.05±0.29	3.8±0.20	0.94±0.05	8.4±3.14	8.2±1.37	0.98±0.16	↔
toluene	$5.9 \cdot 10^3$	9.25±1.47	10.5±1	1.14±0.11	13±2	13±2	1.0±0.15	↓
trimethylbenzene	776	(0.91)	1.25±0.29	(1.38±0.32)	1.5±0.39	1.4	0.93	↓
xylene	$1.4 \cdot 10^3$	9.95±0.1	9.9±0.2	0.99±0.02	24.5±4.9	26±1.96	1.06±0.08	↑
styrene	631	2.6±0.59	2.35±0.1	0.90±0.04	2.7±1.18	2.75±0.88	1.02±0.33	↑
limonene	$2.5 \cdot 10^3$	(1)	5.15±0.29	(5.15±0.29)	(0.94)	3.05±0.69	(3.24±0.73)	↓
butylglycol	n/a	(2.02)	2.6	(1.29)	(1.9)	3	(1.58)	↑
butyldiglycol	n/a	(1.98)	9.1±1.76	(4.61±0.89)	(1.86)	9.65±2.65	(5.19±1.42)	↑
phenol	427	1.9±0.2	2.55±0.1	1.34±0.05	2.85±0.49	3.5±0.20	1.23±0.07	↓
propyleneglycol	n/a	(4.83)	41	(8.5)	NI	NI	n/a	n/a
texanol	n/a	(1.09)	3.2±1.37	(2.95±1.26)	NI	NI	n/a	n/a
acetone	$34.7 \cdot 10^3$	60±7.8	75±5.9	1.25±0.1	135±9.8	125±29.4	0.93±0.22	↓
acetic acid	363	24.5±2.9	39±3.9	1.59±0.16	29±9.8	60.5±20.6	2.09±0.71	↑
benzoic acid	n/a	11	9.4±1.18	0.85±0.11	19.5±12.7	9.9±0.2	0.51±0.01	↔
hexanoic acid	60.3	1.2	2.6±0.59	2.17±0.49	1.25±0.1	1.55±0.29	1.24±0.24	↓
hexadecanoic acid	n/a	NI	NI	n/a	2.85±1.86	(0.81)	(0.28)	n/a
octanoic acid	24	2.65±0.69	3±0.59	1.13±0.22	(0.82)	3.2	(3.93)	↑
nonanoic acid	12.6	3.15±0.69	3.45±1.67	1.1±0.53	1.5±0.98	3.05±0.29	2.03±0.2	↑
decanoic acid	63.1	1.5±0.98	1.45±0.69	0.97±0.46	0.75±0.49	(0.81)	(1.07)	↑
formaldehyde	$1.1 \cdot 10^3$	3.78±3.77	16.85±2.25	4.46±0.60	1.83±0.05	14.40±0.2	7.89±0.11	↑
isopentanal	n/a	1.75±0.69	(0.80)	(0.46)	1.75±0.88	2.5±0.2	1.43±0.11	↑
hexanal	57.5	4.05±0.49	5.7±1.37	1.41±0.34	4.8±0.20	6.85±1.08	1.43±0.22	↑
heptanal	22.9	NI	NI	n/a	(1.41)	3.05±0.69	(2.16±0.49)	n/a
octanal	7.2	4.65±0.29	6.5±0.98	1.4±0.21	4.25±0.88	6.35±0.29	1.49±0.07	↑
nonanal	13.5	14.5±1	18±2	1.24±0.14	9.75±0.49	16±2	1.64±0.2	↑
decanal	5.9	9.55±2.84	11.5±2.9	1.2±0.31	6.3±1.37	10	1.59	↑
undecanal	11.7	(0.87)	1.95±1.27	(2.24±1.46)	NI	NI	n/a	n/a
benzaldehyde	186	4.95±0.29	4.9±0.39	0.99±0.08	5.75±1.67	5.35±0.1	0.93±0.02	↔
butylacetate	933	NI	NI	n/a	1.7±0.98	(0.94)	(0.55)	n/a
butyldiglycolacetate	n/a	(0.67)	4.3±0.59	(6.42±0.88)	(0.63)	5.1±2.16	(8.10±3.42)	↑
hydrocarbons	n/a	1.8±0.2	6.3±3.53	3.5±1.96	3.2±0.59	9.55±0.1	2.98±0.03	↓
acetophenone	$1.8 \cdot 10^3$	2.8	3.1	1.11	2.8±0.98	2.75±0.29	0.98±0.1	↓
benzamide	n/a	NI	NI	n/a	1.75±0.29	(0.81)	(0.46)	n/a
dibuthylphtalate	n/a	NI	NI	n/a	2.4±1.18	(0.62)	(0.26)	n/a
diethylphtalate	n/a	(0.87)	2.7	(3.1)	NI	NI	n/a	n/a
isopropylmirystate	n/a	NI	NI	n/a	(0.55)	1.15±0.1	(2.11±0.18)	n/a
6-methyl-5-hepten-2-one	204	(0.87)	2.9±0.59	(3.33±0.68)	2.15±0.88	3.6±0.39	1.67±0.18	↓
phthalacidanhydride	n/a	2.1±0.59	1.3±0.2	0.62±0.09	1.75±0.49	(0.81)	(0.46)	↔
siloxane	n/a	(0.87)	2.3±0.78	(2.64±0.9)	NI	NI	n/a	n/a

* this column shows only the direction of the effect, independently of whether it is significant or not
NI=compound not identified; n/a=no odour threshold available, or I/O-ratio cannot be estimated, or comparison between conditions cannot be made; ↓=I/O-ratio higher when pollution source was absent in the office; ↑=I/O-ratio higher when pollution source was present in the office; ↔=I/O-ratio in both conditions is below 1

Table 3 Perceived quality of air and sensory pollution loads in the office

Exposure in the office	Perceived air quality (% dissatisfied)		Sensory pollution load (olf/m^2floor)	
	office with pollution source absent	office with pollution source present	office with pollution source absent	office with pollution source present
Upon entering (without bioeffluents)	15	22	0.14	0.25
During exposure (with bioeffluents)	10	12	–	–
Upon re-entering (with bioeffluents)	25	68	0.31	1.92

Table 3 shows subjective assessments of the perceived air quality just after entering the office, during the exposures and upon re-entering the office shortly after each exposure; the perceived quality of the outdoor air caused on average 2% of the subjects to be dissatisfied. Percentages of dissatisfied were calculated using the assessments on the acceptability scale shown in Figure 2 (Gunnarsen and Fanger, 1992).The acceptability of the perceived air quality on first entering and during exposure was lower when the pollution source was present, although the difference did not reach significance (P=0.33). Some adaptation appears to have taken place during the exposure. Eye and nose irritation is not reported here on grounds of space, but was very low, below "slight irritation", and did not differ significantly between conditions. Subjects were therefore effectively "blind" to conditions during the exposure. However, on re-entering the office shortly after the exposure, to assess air quality as if they were visitors, air quality caused 68% to be dissatisfied when the pollution source was present in the office, and only 25% of persons were dissatisfied when the pollution source was absent from the office, the difference being significant at the (P=0.0001) level. As there is no reason to suppose that bioeffluent levels differed systematically between conditions, this result confirms that air quality was lower when the pollution source was present than when it was absent, as expected, even though the subjects, who became adapted to the air quality during the exposures, were not able to perceive the difference between conditions until they returned as visitors. Still, the combined effect of bioeffluents and other air pollutants in the office when the pollution source was present was perceived surprisingly strongly by the subjects re-entering the office shortly after exposure.

Using sensory assessments in the office, the sensory pollution loads were calculated (Fanger, 1988). They confirm (Table 3) that the office with pollution source absent can be characterized as low-polluting, while the office with pollution source present falls in the category of non-low-polluting buildings, according to CEN CR 1752 (1998).

Among perceptions of the environment and SBS symptoms, only the perceived level of illumination, the severity of headaches and the subjective measurements on the effort scale were significantly different between

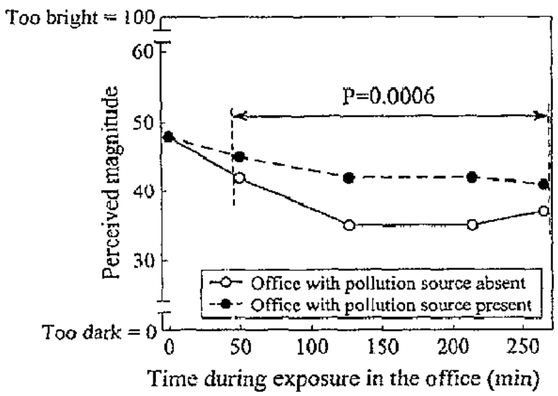

Fig. 5 Perceived illumination when the pollution source was present and absent in the office, as a function of time during exposure in the office

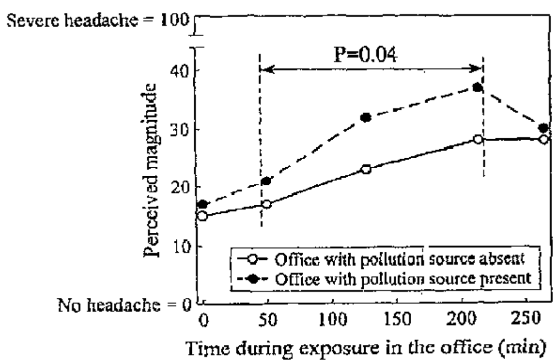

Fig. 6 Severity of headaches experienced in the office when the pollution source was present and absent, as a function of time during exposure in the office

Table 4 The effects on perceptions and symptoms reported by subjects with different personal characteristics compared to the effects observed for the whole group of subjects

Symptom or perception	People sensitive to poor air quality (n=11)	People with SBS-history (n=23)	Whole group (n=30)
Air stuffiness	++	+	NS
Increased dryness of air, airways and eyes	+	NS	NS
Illumination	NS	++	++
Headache	+	++	++
Difficulty in thinking clearly	+	NS	NS
Fatigue	+	NS	NS

++ indicates that the symptom or perception was significantly ($P<0.05$) more intense when the pollution source was present in the office; + indicates that the symptom or perception was more intense at a level approaching significance ($0.05<P\leq0.10$) when the pollution source was present in the office; NS indicates no significant effect

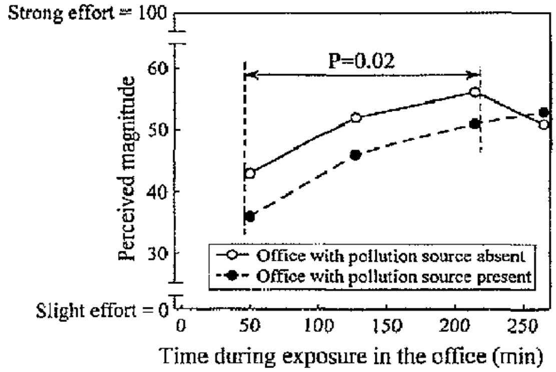

Fig. 7 Subjective measurements on the effort scale when the pollution source was present and absent in the office, as a function of time during exposure in the office

exposure conditions. Figure 5 shows that subjects regarded the office with the pollution source absent as being darker than the office with the pollution source present ($P=0.0006$), the effect occurring from 50 min to the end of exposure (pooled data from this period) thus nearly throughout the whole exposure. This is an unexpected result given that the extra pollution source (carpet), when present, was placed behind a screen, and could therefore not affect the level of illumination at the workstations, and that each workstation was equipped with an individually controlled desk lamp that could be, and actually was, used by subjects during occupation when required.

Severity of headaches was more pronounced in the office with pollution source present ($P=0.04$) but only when subjects added numbers and typed text on a PC (Figure 6), i.e., from 50 to 215 min of exposure (the effect on pooled data from this period). During this time, subjects marked the effort scale significantly closer ($P=0.02$, the effect on pooled data from this time interval) to the "slight effort" end of the scale when the pollution source was present in the office (Figure 7).

To study whether the personal characteristics of subjects could have influenced the symptoms reported, subjects were divided into two groups: subjects who reported themselves to be sensitive to poor air quality (n=11 subjects) and subjects with some reported SBS history (n=23 subjects). The results are presented in Table 4 and indicate that these more sensitive subgroups generally experienced more symptoms, especially those pertaining to sensory perceptions and mental exertion. The effects for the subjects with some SBS history were very similar to those observed for the whole group, as almost all subjects (23 out of 30) had some SBS history.

The effects on subjects' performance are summarized in Table 5 only for the tests for which the difference between conditions approached significance ($0.05<P\leq0.10$) or was significant ($P<0.05$). The difference in subjects' experience, training, intellectual skills, etc. was excluded from the effects on performance as all statistical analyses of the performance tests were carried out as within-subject comparisons. All of the effects in Table 5 are in the expected direction, implying a negative impact of the presence of the pollution source in the office on subjects' performance.

Table 5 Summary of the effects on performance

Test	Effect	Description	P-value
Text typing	6.5%	fewer characters typed when the pollution source was present	0.003
Text typing	5%	more typing errors when the pollution source was present	0.10
Addition	3.8%	smaller increase of the number of added units when the pollution source was present	0.045
Logical reasoning	3.4%	smaller increase of reaction time when the pollution source was present	0.08
Serial addition	2.5%	smaller increase of correctly added digits when the pollution source was present	0.06
Stroop	3.1%	smaller increase of speed when the pollution source was present	0.10

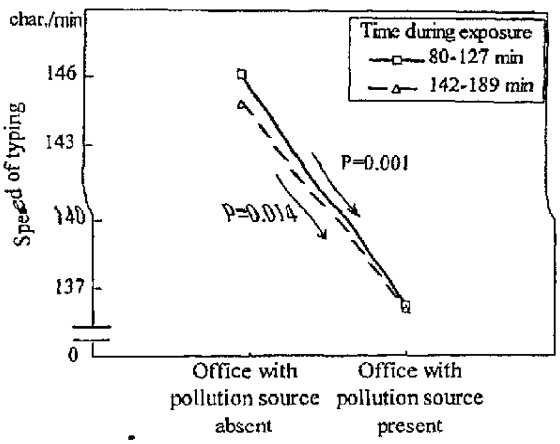

Fig. 8 Speed of typing during the first (80–127 min) and second (142–189 min) performance of the text typing task, as a function of the presence or absence of the pollution source in the office. Subjects typed 6.5% fewer characters when the pollution source was present in the office

The strongest effect on subjects' performance was observed for the test involving text typing, which is a universal office task. Subjects typed fewer characters per minute when the pollution source was present in the office. This effect was highly significant ($P=0.003$) and was significant both when subjects typed text for the first and the second time during exposure (Figure 8). The task is so common that no learning effect whatever was observed. Subjects also made more typing errors when the pollution source was present in the office, but as shown in Table 5 this effect did not reach formal significance ($P=0.10$).

The negative effects of the pollution source for the other tests shown in Table 5, i.e., addition, logical reasoning, serial addition and Stroop, were smaller than for the typing task. They did not show, however, the main effect of the condition on performance (i.e., a change of speed or accuracy due to the presence or absence of the pollution source), but rather a change (increase or decrease) in performance between successive tests during each exposure. Presence of the pollution source in the office tended to reduce the learning effect observed during each of these tests.

Discussion

The European report CEN CR 1752 (1998) strongly recommends that low-polluting building materials should be selected when a building is designed. The idea is to improve the perceived air quality and decrease the required ventilation. The present study supports the idea behind CEN CR 1752. Even removing a source causing a chemically barely measurable air pollution improved the perceived air quality, decreased SBS symptoms, and improved the performance of office workers even in half-day exposures. These results were obtained in a real office with windows and access to daylight. The same group of 30 impartial subjects were exposed in the office in which a pollution source was introduced or removed, each time for 265 min, performed simulated office work and remained thermally neutral. Moreover, in contrast with previous intervention studies (Norbäck and Torgén, 1989; van Beuningen et al., 1994; Pejtersen et al., 1999), the subjects were blind to the intervention, so their expectations could not have influenced the observed effects. Females were selected as subjects since they constitute a risk group in indoor environments, consistently reporting more SBS symptoms than males (Mendell, 1993). The observed effects were exclusively caused by the reversible intervention in the office consisting of introducing or removing the pollution source, a 20-year-old carpet removed from an office building with a history of occupant complaints; all other parameters of the indoor environment in the office, including air temperature, relative humidity, air velocity, noise level and ventilation rates, had similar levels whether the pollution source was present or absent.

The condition in which the pollution source (the carpet) was present in the office elevated the severity of headaches; carpets in the working environment have previously been associated with a higher risk of SBS symptoms (Norbäck and Torgén, 1989; Fisk et al., 1993; Mendell, 1993; Pejtersen et al., 1999). However, in the present experiment, the difference in prevalence of headaches was observed only during work requiring concentration – text typing and addition of numbers. When subjects performed the PAB and the knowledge and recall test, no difference in prevalence of headaches could be observed. This was also the case towards the end of the exposure (Figure 6); the latter can be attributed to a positive mood change in anticipation of the end of the session, counteracting fatigue. The present results thus imply that the risk of some SBS symptoms may be increased during concentrated office work in the presence of pollution sources.

Subjects performed less well when the pollution source was present in the office, they experienced worse headaches, and they marked the effort scale closer to the "slight effort" end. If it is assumed that the effort scale was used as intended, to indicate task difficulty, all that can be concluded is that subjects may have been wrong. However, if subjects used the effort scale to report how much effort they had exerted, these

same results can be interpreted to indicate that subjects exerted less effort when the pollution source was present in the office because they had more severe headaches, and that this inadequate level of effort resulted in the significantly reduced performance that was observed. An analogous effect of moderate heat stress on effort and work rate during mental performance is evident in the experiment of Pepler and Warner (1968), in which headaches were not reported. In this and the present experiment, a reasonable *post factum* interpretation would seem to be that work rates were low because subjects were disinclined to exert the necessary effort to maintain performance under slightly adverse conditions, although they clearly could have done so.

The subjects typed 6.5% less text when pollution source was present in the office, which means that it would have taken them ca. 3 min longer to continuously type the text. This estimate does not take into account the extra time required for proof-reading and corrections, which would also be longer in this office considering that the number of typing errors was on average ca. 5% higher than in the condition with pollution source absent. At the same time, no learning effect was observed for typing. Other performance tests showed considerable learning, which was reduced when the pollution source was present in the office, even though subjects had completed 10 practice sessions in a neutral environment. The above findings indicate that simulated work of long duration seems to be more sensitive to environmental effects than diagnostic tests of short duration and can thus be recommended for use in future studies of this kind. It should also be noted that in this study the comparison in terms of performance was almost a blind one since the difference in perceived air quality between conditions corresponded to 12% and 10% of the subjects being dissatisfied during exposures, a difference that is both small and not statistically significant.

In the present study, typing text took ca. 6% longer when the pollution source was present in the office and when the severity of headaches was elevated. This effect is 3 times higher than was assumed in estimating the national economic cost of SBS due to decreased productivity, which was based on self-reported productivity decrements (Fisk and Rosenfeld, 1997). In the present experiment, text typing performance was measured objectively. It is probably the most common task performed in offices, although no more than half of any present-day employee's time is probably used in typing text.

The difference in the perceived illumination in the office with the pollution source present and absent is unexpected and difficult to explain. Although the level of illumination was not measured during the experiment, it is unlikely that any differences occurred between conditions, especially considering that the carpet used as the pollution source did not absorb any of the daylight reaching the occupied area and that subjects could individually control the desk lamp at each workstation. The perception that it was darker when the pollution source was absent in the office may simply indicate that subjects felt more relaxed and incorrectly attributed this feeling to a difference in illumination level, bright light being a powerful arousing factor.

Slightly higher concentrations of aldehydes, ketones and organic acids, which are strong odorants (Devos et al., 1990) and expected to be strong irritants (Wolkoff et al., 1997), were measured in the condition with the pollution source present in the office (Table 2). These compounds are expected to be the products of reactions with ozone taking place indoors (Weschler and Schields, 1997). Aldehydes in particular can be produced by the reaction of the emissions from carpets with ozone (Weschler et al., 1992), implying that such reactions may have occurred in the present experiment when the carpet was present in the office. It should also be recalled that the present method of chemical measurement and analysis does not allow the measurement of compounds which are unstable or which occur at concentrations below detection limits. Although not identified, the combined effect of many such compounds may still have a significant impact on humans. The sensory measurements showed thus a difference in the sensory loads (Table 3). With an estimated sensory load from the six subjects of 0.16 olf/m^2 floor, the combined load of persons and the office with the pollution source absent agreed well with addition of the two sources. When bioeffluents from the persons combined with the pollution source when it was present in the office, the total sensory load was much higher than predicted by adding the sensory loads from the building and the persons, implying that chemical reactions or synergistic sensory effects may have occurred.

In the present experiment, subjects considering themselves as more sensitive to poor air quality tended to respond more to the difference between conditions than the group as a whole. This is apparent in Table 4. Self-reported sensitivity was also found to be significantly associated with prevalence of symptoms among the occupants of 11 sick office buildings in Sweden (Norbäck et al., 1990), and hence may be considered as a risk factor for SBS symptoms.

Wyon (1996) has suggested a new approach to productivity research. A specific mechanism to explain

any effect on performance of a change in environmental conditions should be formulated by defining a chain of falsifiable hypotheses, each of which must be true for the mechanism to be valid. This approach can be exemplified by the present study, which hypothesized that increased air pollution affects human performance. The mechanism may be expressed as the following chain of linked hypotheses: 1) air pollutant levels were raised by the presence of the carpet; 2) perceived air quality was reduced by the raised pollutant levels; 3) lower perceived air quality caused headaches; 4) headaches caused subjects to exert less effort; and 5) lower levels of effort led to a reduced work rate in the text typing task. Although it could not be clearly shown by chemical analysis that air pollutant levels were indeed raised when the pollution source was present in the office, it is a reasonable assumption that they were, as perceived air quality was reduced in this condition. Steps 2–5 of the mechanism are compatible with the significant results of the present study. Similar mechanisms should be proposed and verified in future experiments with different environmental stressors.

A limitation of the present experiment is that only young female subjects were recruited. As they were students, they were not representative of office workers. Office employees performing especially clerical and secretarial work complain of more symptoms, either due to the type of work (e.g., paper handling, working with a PC) or to increased exposures (e.g., emissions from copier, fax) (Mendell, 1993). Atopic people suffering from asthma, hay fever, allergy, chronic bronchitis or eczema also report more symptoms than people with normal sensitivity (Sundell, 1994). Extrapolating the present results to atopic people and office workers, a stronger effect would be expected than was observed in the present experiment. Future experiments should study other subpopulations of subjects, systematically varying the age of subjects, their health, sensitivity and occupation.

Two exposure conditions in the present experiment, with the pollution source present and absent in the office, were created in a simulated environment, the subjects thus not being exposed in their own working environment. Although every effort was made to provide a natural and typical office environment, it may still have been perceived as different from that of a normal workplace. Further studies of a possible contextual effect would be useful. Moreover, people in the present study occupied the office only for two periods lasting ca. 4.4 h each. In real life, people are repeatedly exposed to the working environment for 8 h every working day, 5 days per week, 4 weeks per month for many years. Recurrent exposure may be an important factor amplifying symptom prevalence and future experiments should address this issue.

Conclusions

- The perceived air quality was improved, SBS symptoms decreased and productivity increased in the condition corresponding to a low-polluting building in comparison with the condition typical of a non-low-polluting building (as defined by CEN CR 1752), with otherwise identical indoor environmental conditions.
- CEN CR 1752 provides a strong incentive to design for low-polluting buildings. The present results document the advantages of low-polluting buildings for human comfort, SBS symptoms and productivity.
- A mechanism relating reduced perceived air quality to decreased human performance was demonstrated. Mechanisms of this kind should be investigated in future studies with other environmental stressors, longer exposures and other subpopulations than those used in the present study.

Acknowledgements

This work has been supported by the Danish Technical Research Council (STVF) as part of the research programme of the International Centre for Indoor Environment and Energy established at the Technical University of Denmark for the period 1998–2007. We would like to express our thanks to the anonymous reviewers for their constructive comments.

References

Arens, E., Xu, T., Miura, K., Hui, Z., Fountain, M. and Bauman, F. (1998) "A study of occupant cooling by personally controlled air movement", *Energy and Buildings*, 27, 45–59.

ASHRAE (1997) *Fundamentals*, Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Baker, E.L., Letz, R.E., Fidler, A.T., Shalat, S., Plantamura, D. and Lyndon, M. (1985) "A computer-based neurobehavioral evaluation system for occupational and environmental epidemiology: Methodology and validation studies", *Neurobehavioral Toxicology and Teratology*, 7, 369–377.

Berglund, B., Berglund, U. and Engen, T. (1992a) "Can sick buildings be assessed by testing human performance in field experiments?", *Environment International*, 18, 221–229.

Berglund, B., Brunekreef, B., Knöppel, H., Lindvall, T., Maroni, M., Mølhave, L. and Skov, P. (1992b) "Effects of indoor air pollution on human health", *Indoor Air*, 2, 2–25.

van Beuningen, M.F., Clausen, G., Pejtersen, J. and Fanger P.O. (1994) "Reducing the sensory air pollution load in a building by renovation". In: Banhidi, L., Farkas, L., Magyar, Z. and Rudnai, P. (eds) *Proceedings of Healthy Buildings '94*, Budapest, Vol. 2, pp. 413–418.

Bluyssen, P.M., de Oliveira Fernandes, E., Groes, L., Clausen, G., Fanger, P.O., Valbjørn, O., Bernhard, C.A. and Roulet, C.A. (1996) "European indoor air quality audit project in 56 office buildings", *Indoor Air*, 6, 221–238.

Brown, S.K., Sim, M.R., Abramson, M.J. and Gray, C. (1994) "Concentrations of volatile organic compounds in indoor air", *Indoor Air*, 4, 123–134.

Bælum, J., Andersen, I., Lundqvist, G.R., Mølhave, L., Pedersen, O.F., Væth, M. and Wyon, D.P. (1985) "Response of solvent exposed printers and unexposed controls to six-hour toluene exposure", *Scandinavian Journal of Work, Environment & Health*, 11, 271–280.

CEN CR 1752 (1998) *Ventilation for buildings: Design criteria for the indoor environment*, Brussels, European Committee for Standardization.

de Dear, R.J. and Fountain, M.E. (1994) "Field experiments on occupant comfort and office thermal environments in a hot-humid climate", *ASHRAE Transactions*, 100, 457–475.

Devos, M., Patte, F., Rouault, J., Laffort, P. and van Gemert, L.J. (1990) *Standardized Human Olfactory Thresholds*, Oxford, IRL Press.

Fanger, P.O. (1988) "Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors", *Energy and Buildings*, 12, 1–6.

Fanger, P.O., Lauridsen, J., Bluyssen, P. and Clausen, G. (1988) "Air pollution sources in offices and assembly halls quantified by the olf unit", *Energy and Buildings*, 12, 7–19.

Fisk, W.J., Mendell, M.J., Daisey, M.J., Faulkner, D., Hodgson, A.T. and Macher, J.M. (1993) "The Californian healthy building study, phase 1: A summary". In: Saarela, K., Kalliokoski, P. and Seppänen, O. (eds) *Proceedings of Indoor Air '93*, Helsinki, The 6th International Conference on Indoor Air Quality and Climate, Vol. 1, pp. 279–284.

Fisk, W.J. and Rosenfeld, A.H. (1997) "Estimates of improved productivity and health from better indoor environments", *Indoor Air*, 7, 158–172. [Errata in *Indoor Air* 1998, 8, 301.]

Gunnarsen, L. and Fanger, P.O. (1992) "Adaptation to indoor air pollution", *Energy and Buildings*, 18, 43–54.

Hall, H.I., Leaderer, B.P., Cain, W.S. and Fidler, A.T. (1991) "Influence of building-related symptoms on self-reported productivity". In: *Proceedings of Healthy Buildings IAQ '91*, Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers, pp. 33–35.

ISO (1988) *Sensory analysis – Methodology – Ranking test*, Geneva, International Organization for Standardization (ISO 8587).

ISO (1993) *Sensory analysis – General guidance for the selection, training and monitoring of assessors – Part 1: selected assessors*, Geneva, International Organization for Standardization (ISO 8586-1).

Leinster, P. and Mitchell, E. (1992) *A review of indoor air quality and its impact on the health and well-being of office workers*, Directorate-General Employment, Industrial Relations and Social Affairs (EUR 14029 EN).

Mendell, M.J. (1993) "Non-specific symptoms in office workers: a review and summary of the epidemiologic literature", *Indoor Air*, 3, 227–236.

Montgomery, D.C. (1991) *Design and analysis of experiments*, 3rd ed., New York, John Wiley and Sons.

Mølhave, L. and Møller, J. (1978) "The atmospheric environment in modern Danish dwellings - measurements in 39 flats". In: Fanger, P.O. and Valbjørn, O. (eds) *Proceedings of the First International Indoor Climate Symposium*, Copenhagen, Danish Building Research Institute, pp. 171–186.

Mølhave, L. (1982) "Indoor air pollution due to organic gases and vapours of solvents in building materials", *Environment International*, 8, 117–127.

Mølhave, L., Bach, B. and Pedersen, O.F. (1986) "Human reactions to low concentrations of volatile organic compounds", *Environment International*, 12, 167–175.

New York State Commission on Ventilation (1923) *Report of the New York State Commission on Ventilation*, Dutton, New York, New York State Commission on Ventilation.

Norbäck, D. and Torgén, M. (1989) "A longitudinal study relating carpeting with Sick Building Syndrome", *Environment International*, 15, 129–135.

Norbäck, D., Michel, I. and Widström, J. (1990) "Indoor air quality and personal factors related to the sick building syndrome", *Scandinavian Journal of Work, Environment & Health*, 16, 121–128.

Nunes, F., Menzies, R., Tamblyn R.M., Boehm, E. and Letz, R. (1993) "The effect of varying level of outdoor air supply on neurobehavioural performance function during a study of sick building syndrome (SBS). In: Saarela, K., Kalliokoski, P. and Seppänen, O. (eds) *Proceedings of Indoor Air '93*, Helsinki, The 6th International Conference on Indoor Air Quality and Climate, Vol. 1, pp. 53–58.

Otto, D.A., Hudnell, H.K., House, D.E., Mølhave, L. and Counts, W. (1992) "Exposure of humans to a volatile organic mixture. I. Behavioral assessment", *Archives of Environmental Health*, 47, 23–30.

Otto, D., Hudnell, K., House, D. and Prah, J (1993) "Neurobehavioral and subjective reactions of young men and women to a complex mixture of volatile organic compounds". In: Saarela, K., Kalliokoski, P. and Seppänen, O. (eds) *Proceedings of Indoor Air '93*, Helsinki, The 6th International Conference on Indoor Air Quality and Climate, Vol. 1, pp. 58–65.

Pejtersen, J., Clausen, G., Sørensen, J., Quistgaard, D., Iwashita, G., Zhang, Y., Onishi, T. and Fanger, P.O. (1991) "Air pollution sources in kindergartens". In: *Proceedings of Healthy Buildings – IAQ '91*, Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers, pp. 221–224.

Pejtersen, J., Brohus, H., Hyldgaard, C.E., Nielsen, J.B., Valbjørn, O., Hauschildt, P., Kjærgaard, S.K. and Wolkoff, P. (1999) "The effect of renovating an office building on occupants comfort and health". In: *Proceedings of Indoor Air '99*, Edinburgh, The 8th International Conference on Indoor Air Quality and Climate (in press).

Pepler, R.D. and Warner, R.E. (1968) "Temperature and learning: An experimental study", *ASHRAE Transactions*, 74, 211–219.

Pettenkofer, M.V. (1858) *Über den Luftwechsel in Wohngebäuden*, Munich, Litterarisch-Artistische Anstalt der J.G. Cotta'schen Buchhandlung.

Raw, G.J., Roys, M.S. and Leaman, A. (1990) "Further findings from the office environment survey: Productivity". In: Walkinshaw, D.S. (ed) *Proceedings of Indoor Air '90*, Toronto, The 5th International Conference on Indoor Air Quality and Climate, Vol. 1, pp. 231–236.

Siegel, S. and Castellan, N. J. (1988) *Nonparametric Statistics for the Behavioral Sciences*, New York, McGraw Hill.

Sundell, J. (1994) "On the association between building ventilation characteristics, some indoor environmental exposures, some allergic manifestations and subjective symptom reports", *Indoor Air*, Supplement 2, 1–148.

Thorne, D.R., Genser, S.G., Sing, H.C. and Hegge F.W. (1985) "The Walter Reed performance assessment battery", *Neurobehavioral Toxicology and Teratology*, 7, 415–418.

Thorstensen, E., Hansen, C., Pejtersen, J., Clausen G. and Fanger, P.O. (1990) "Air pollution sources and indoor air quality in schools". In: Walkinshaw, D.W. (ed) *Proceedings of Indoor Air '90*, Toronto, The 5th International Conference on Indoor Air Quality and Climate, Vol. 1, pp. 531–536.

Wargocki, P. and Fanger, P.O. (1997) "Impact of changing the floor material on air quality in an office building". In:

Woods, J.E., Grimsrud, D.T. and Boschi, N. (eds) *Proceedings of Healthy Buildings/IAQ '97*, Washington, DC, Vol. 2, pp. 243–248.

Weschler, C.J., Hodgson, A.T. and Wooley, J.D. (1992) "Indoor chemistry: Ozone, volatile organic compounds, and carpets", *Environmental Science Technology*, 26, 2371–2377.

Weschler, C.J. and Shields, H.C. (1997) "Potential reactions among indoor pollutants", *Atmospheric Environment*, 31, 3487–3495.

Wolkoff, P., Clausen, P.A., Jensen, B. Nielsen, G.D. and Wilkins, C.K. (1997) "Are we measuring the relevant indoor pollutants?", *Indoor Air*, 7, 92–106.

World Health Organization (1982) *Indoor Air Pollutants: Exposure and Health Effects*, Copenhagen, WHO Regional Office for Europe (Euro Reports and Studies no. 78).

Wyon, D.P. (1969) *The effects of moderate heat stress on the mental performance of children*, Stockholm, Swedish Building Research Report Series, D8/69.

Wyon, D.P., Fanger, P.O., Olesen, B.W. and Pedersen, C.J.K. (1975) "The mental performance of subjects clothed for comfort at two different air temperatures", *Ergonomics*, 18, 359–374.

Wyon, D.P. (1994) "Symptom intensity feedback testing (SIFT): Behavioural science may be able to provide the key to curing sick buildings". In: Banhidi, L., Farkas, I., Magyar, Z. and Rudnai, P. (eds) *Proceedings of Healthy Buildings '94*, Budapest, Vol. 3, pp. 42–47.

Wyon, D.P. (1996) "Indoor environmental effects on productivity", In: *Proceedings of IAQ '96*, Atlanta, GA, American Society for Heating Refrigerating and Air-Conditioning, pp. 5–15.

Yaglou, C.P., Riley, E.C. and Coggins, D.I. (1936) "Ventilation requirements", *ASHVE Transactions*, 42, 133–162.

Yaglou, C.P. (1955) "Ventilation requirements for cigarette smoke", *ASHAE Transactions*, 61, 25–32.